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Uses and Usefulness of Paraquat

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1 Paraquat was discovered in 1955 and introduced to the market place in 1962. During the 23 years between introduction and the present day numerous successful practical uses of the herbicide have been developed. In addition the characteristics of the chemical have allowed significant changes to be made in the ways that some crops are grown.
2 Paraquat is a relatively non-selective foliage-applied contact herbicide. It is inactivated on contact with almost all naturally occurring soils and it was this property, perhaps above all others, that provided the greatest breakthrough in chemical weed control at the time of its discovery.
3 Inactivation on contact with soil means that no biologically active residues remain in the soil, thus allowing planting or sowing to be carried out almost immediately after spraying. Although the non-systemic (contact) property of paraquat makes it less than ideal for the long-term control of perennial weeds, the same property is of real advantage when parts of crop plants are sprayed accidentally, for usually only the part receiving the spray is affected.
4 Total annual usage of all herbicides in agriculture and horticulture in England and Wales, UK, over the period of 1980–1983 has been estimated at 26 360 tonnes used on $12\,402 \times 10^3$ ha (1 hectare $= 1 \times 10^4\ m^2$). For paraquat (not including its mixtures with diquat and monolinuron) 270 tonnes were sprayed over 392 218 ha/year. It is estimated from sales records that in Europe 5×10^6 ha are sprayed annually with paraquat.
5 The paper reviews the need for the use of herbicides and the properties that are important for particular crop–weed situations, but concentrates on the properties of paraquat that make it an essential agent of weed control in many areas of agriculture, horticulture and forestry.

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Introduction

Weeds have existed as long as man but it was the introduction of rotation, after the enclosure of land, that made weed control an important element of efficient husbandry. By the mid-nineteenth century the cleaning crops of turnips and potatoes provided years in the rotation when weed control was possible by using hand labour. Later, when that became less economic, various mechanical devices, powered at first by animals and then by engines, were invented. The plough, first used in the UK before the Romans came, remained throughout this period a major weapon in weed control through its ability to bury growing weeds to depths from which it was difficult for them to emerge (Roberts, 1982).

Although several inorganic chemicals were in use for weed control early in the twentieth century and in the 1930s some organics were introduced for weed control in cereals, the real story of weed control by the use of chemicals did not begin until after World War II when the release of 4-chloro-2-methylphenoxy-acetic acid (MCPA) and 2,4-dichlorophenoxyacetic acid (2,4-D) began a real revolution (Kirby, 1980). These herbicides were revolutionary because they were selective and gave control of many broad-leaved weeds in growing cereal crops. Quite suddenly crops (cereals) that had been the dirty crops of rotations because of the impossibility of weeding them, became, potentially, the cleaning crops. Although that dream was never realized fully, there was sufficient promise for some agronomists to begin to question the need for the plough.

Discovery of new herbicides

The success of the early phenoxyacetic acid herbicides triggered an enormous effort by the chemical industry to discover and develop chemicals with properties that allowed successful chemical weed control

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in other crops. The approach was rewarded and in the UK there was an increase from 11 chemicals (104 products) approved in 1958 to 44 (277 products) 10 years later and 73 (450 products) by 1975 (Roberts, 1982). Paraquat (1,1′-dimethyl-4,4′-bipyridylium) was discovered in 1955 and brought to the market-place in 1962. A monograph of the bipyridinium herbicides has been published (Summers, 1980).

Properties of herbicides

A much fuller review of the properties of herbicides is available in Roberts (1982).

Selectivity
Some herbicides are selective, that is, they may safely be sprayed at a recommended dose on mixtures of crops and weeds. The crop is not or is scarcely affected but the weeds are killed or seriously debilitated. Other herbicides are non-selective and are used either when the crop is absent or with methods which protect the crop physically. Paraquat is relatively non-selective, killing a wide range of annual grass and dicot weeds and the tops of established perennial weeds (Anon., 1984).

Modes of activity
Some herbicides are only effective in the soil or on the soil surface since they enter plants, principally, through the roots or emerging shoots (soil-active herbicides). Some of these may have long residual activity. Yet other materials are best applied to the foliage of weeds, but again these compounds divide into two groups: those which enter the leaves and thence the long-distance phloem transport system (foliage-applied translocated herbicides) and those which enter the leaves but are not exported from them (foliage-applied contact herbicides). As occurs in every classification there are herbicides which fall into more than one category but paraquat is, save under some very extreme circumstances, a foliage-applied contact herbicide.

Persistence
Persistence of herbicides in plants, soil and the environment also varies and, environmental implications apart, differences in persistence can be exploited in practice. Lack of persistence may arise because the molecule is degraded rapidly by, for example, microbial activity or sunlight or because the molecule is made unavailable for significant biological activity due to adsorption in the soil (or in the plant). Paraquat is broken down rapidly in sunlight and is so strongly adsorbed by clays and, to a lesser degree, by organic matter that it becomes biologically inactive on contact with most soils (Calderbank, 1968). This last property, as we shall see, provides, above all others, the key to the usefulness of paraquat.

Rainfastness
Many foliage-applied herbicides are liable to be washed off leaves if rain falls within a few hours of spraying with a consequent loss of effectiveness and money. Paraquat, however, is rainfast within minutes of application. This property reduces the operator's dependence on weather and allows great precision in the timing of applications.

Mode of action
Photosynthesis, that takes place in the green parts of plants when they are irradiated with sunlight, generates electrons which reduce the paraquat ion to a free radical which is rapidly reoxidized. During the re-oxidization a superoxide is generated and this damages membranes and cytoplasm and leads to rapid death of cells (Calderbank, 1968).

Summary

Paraquat is a relatively non-selective rainfast foliage-applied contact herbicide with undetectable biologically active persistence in almost all soils. Its ability to cause rapid kill is dependent on the photosynthetic activity of plants.

Usefulness of paraquat

Figure 1 shows, diagrammatically, 12 of the situations in which farmers and growers seek to effect weed control. Paraquat is of no use for any of the models in column A, simply because the weed is buried in the soil and the herbicide cannot reach the target. However, where weed seedlings are emerged and the grower wishes to sow or plant a crop as soon as possible after controlling the weeds (B1) the properties of paraquat are ideal: kill is assured and the herbicide leaves no biologically active residue. This model (B1) has another context, one where the weeds are not seedlings but established plants that may include crop plants but where, after kill of all vegetation, either cultivation or direct drilling or planting of a new crop may follow very shortly after paraquat is applied. Again it is the lack of biologically active residues that permits almost immediate sowing or planting.

Because paraquat is not translocated, it is not the first-choice herbicide for perennial weed control (Cl). The more recently introduced glyphosate [*N*-(phosphonomethyl)glycine] shares with paraquat and diquat the property of being biologically inactive in soil but glyphosate is a foliage-applied translocated herbicide. Nevertheless, paraquat sprayed on to the foliage of perennial weeds acts as a chemical

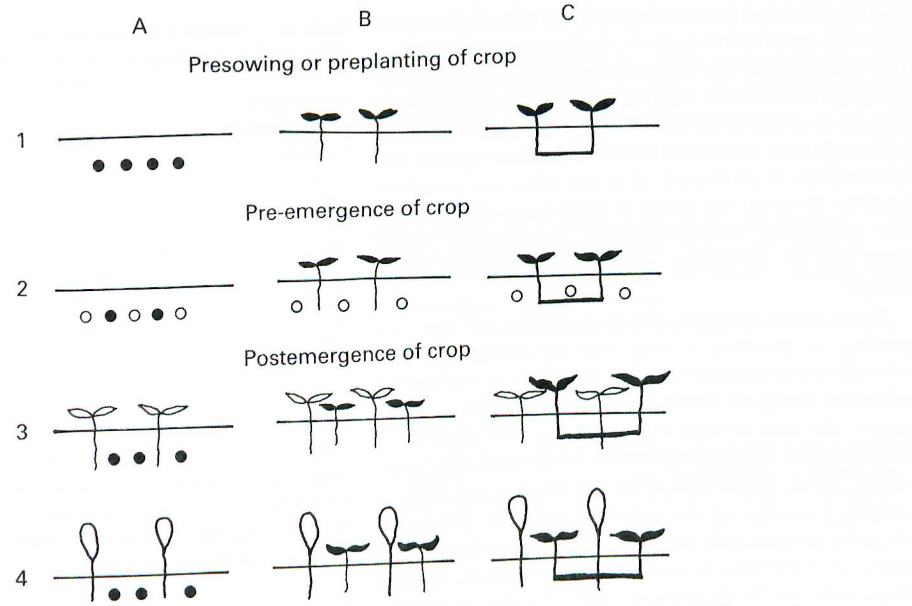

Figure 1 Diagrams illustrating 12 crop–weed situations. Columns: A, weeds present as seeds; B, weeds present as emerged seedlings; C, weeds present as perennials. Rows: 1, crop not yet sown or planted; 2, crop sown, but not yet emerged; 3, crop seedlings emerged; 4, crop perennial, often woody. ● = weed seed; ○ = crop seed; = weed seedling; = crop seedling; = crop plant; = perennial weed [after H. A. Roberts (1982) Weed Control Handbook, vol. I, *Principles*, 7th edn. Oxford: Blackwell Scientific Publications]

scythe and destroys the above-ground parts of the weed and the use of herbicide on non-cropped land relies on this property. Regular applications of paraquat can lead, through attrition, to the control of perennial weeds.

In situations where the crop has been sown, weeds have emerged but the crop has not (B2, Figure 1), paraquat becomes a crucially important herbicide in the armoury. Yet again because of the speed of the inactivation process weeds can be killed only hours before the seedling crop plants emerge, thus giving the latter maximum competitive advantage. Similarly, areas planted to bulbs may be sprayed up to 3 days before the bulbs emerge (and again at the end of the growth cycle of the bulbs when all green foliage has disappeared). Care must, however, be exercised when the bulbs are grown on very sandy soils for the inactivation process may not be as effective as on heavier soils. In hops weed control is also possible before the plants emerge, in lucerne before the crop commences spring growth or after a harvest has been taken when little leaf is present. Perhaps the extreme examples of pre-emergence spraying with paraquat is with potatoes where up to 40% emergence of main-crop potatoes can be permitted before spraying. The emerged potato shoots are damaged but the resilience of the plant with its storage organ below ground, coupled with the failure of paraquat to be translocated down to the critical below-ground organs, allows recovery and makes ultimate economic sense because the crop emerges into what is effectively a weed-free environment. A foliage-applied non-selective translocated herbicide would be useless for such a situation.

Where the crop has emerged, the non-selectivity of paraquat precludes its use as an overall spray of both crop and weed. However, when crops are grown in rows it is possible, by using guarded no-drift sprayers, to kill weeds between the rows with paraquat (B3, Figure 1). Slight accidents where odd leaves of the crop plants are sprayed are not critical because the contact action means that only the sprayed leaves are killed. A rather more sophisticated practice, but one that depends on the same principles, has been developed for use in strawberries. The production of runners each year is a nuisance in a strawberry crop grown for fruit. By using carefully directed guarded sprays it is possible to kill the daughter plants with paraquat as the agent. Lack of translocation means that the mother plants are not affected by the spray and the adsorption of the chemical by the soil prevents leaching and possible damage to roots.

When crop plants are perennial and become woody with the lower parts of the stem completely covered in dead bark herbaceous weeds may be controlled safely with paraquat because the herbicide does not penetrate bark readily; it is adsorbed on to dead organic matter. This natural protection of the

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crop has allowed the development of uses of paraquat for weed control in top fruit, in forestry and in vines (B4, C4; Figure 1). The use of paraquat to control unwanted suckers in vines is based on the principles, already described, for runner control in strawberries. Although bark is a useful physical defence against the penetration of paraquat, it is not wise nor standard practice to spray the bases of crop trees deliberately but accidental contamination, particularly when trees are in dormancy, has a considerable safety margin.

Until quite recently, the preparation of land for sowing or planting a crop was by ploughing and extensive cultivation of the soil. For a variety of reasons, many of them not directly relevant to this paper, the need to treat soil in this way was challenged and analyses of real needs were made from first principles. First, at the end of the life of any crop there is usually a residue of live and dead rubbish, some of it of crop origin and some of it representing weed material which has persisted beyond harvest. If these materials can be destroyed other than by ploughing then the plough is not required. Secondly, to establish a crop from seed, the physical structure of the soil must be suitable for the process of germination, emergence and subsequent growth. One of the aims of mechanical cultivation was to produce a 'tilth', although many soils which have grown crops already have an excellent structure at least in the uppermost layer. Thirdly, crop seedlings should, ideally, emerge into a weed-free environment. Cultivation is but a very temporary way of achieving this aim; herbicides are much more effective.

Against this background exciting research programmes, practical and fundamental, were initiated. The extreme variant, termed direct drilling, involves simply the effective clearance of old crop residues and weeds followed by the sowing of the seed of the new crop either directly on to the surface or inserted mechanically at a predetermined depth. This technique is energy conserving, very rapid and does not disturb the soil profile. Heavy machinery, which tends to destroy soil structure by compaction, is not needed.

The success of direct drilling varies with soil type (Anon., n.d.) and it is not successful universally.

Table 1 Summary of uses of paraquat

Lucerne	Minimum cultivation
Bulbs	Direct drilling
Potato	Stubble treatments
Row crops	Killing grassland before ploughing
Soft fruit	Forest nurseries
Hops	Forest plantations
Vines	Non-cropped land
Top fruit	

Table 2 Estimated annual use of paraquat over the years 1980–1983 in England and Wales, UK

Crop type	*ha/year*
Cereals	179 628
Grass	91 943
Other arable	76 138
Vegetables, bulbs	20 995
Top fruit	8894
Soft fruit	5995
Hops	4765
Hardy nursery stock	3706
Protected crops	154
Total	392 218

Values are spray-hectares [J. M. A. Sly (1985). Pesticide usage survey report (preliminary) 41. Review of usage of pesticides in agriculture and horticulture in England and Wales 1980–1983. Ministry of Agriculture, Fisheries and Food, London]

In consequence, a series of other techniques referred to as minimum or reduced cultivations have been developed. For both direct drilling and minimum cultivation a wide range of equipment and systems has been developed. Further information about the science and the practice of this whole area is available (e.g. Halliday, 1975; Allen, 1981; Butterworth, 1985) and comparisons have been made of the relative productivity of the systems (Matthews, 1975). Direct drilling a crop takes only 17.3% of the time that ploughing and cultivation would need.

This over-simplified picture of the cultivation revolution has been painted because its success has depended, although not exclusively, on the properties of paraquat; in particular, the speed of action, rainfastness, lack of selectivity and, above all, the non-residual activity of this herbicide have been crucial.

Use and uses

Most of the uses of paraquat have been identified in the previous section but they are presented as a list in Table 1. Two leaflets published by Plant Protection Division of ICI are particularly valuable as general accounts of the uses and usefulness of paraquat (Anon., 1981, 1983).

Paraquat is used at rates of between 0.7 and 8.5 litres of Gramoxone (the commercial product)/ha (1 hectare = 1×10^4 m^2) which is equivalent to about 14–170 g of paraquat/ha. In England and Wales, UK, over the period 1980–1983 it has been estimated that paraquat was sprayed on 392 218 h/year (Sly, 1985). Estimates from sales records suggest that in Europe 5×10^6 ha are sprayed annually with paraquat. In Table 2 is given a breakdown of the annual use in England and Wales; equivalent details for Europe as a whole do not appear to be available readily.

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Postscript

I have attempted in this paper to illustrate the usefulness of paraquat and to show how its uses depend on the combinations of properties which are unique to the bipyridilium herbicides. The particular advantage of paraquat over diquat is the significantly greater ability of paraquat to control grass weeds.

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